Lecture 10. Satellite measurements

Satellite terminology

- **Platform.** The satellite infrastructure.
  Examples: TOMS instrument on Nimbus-7 (1978-1993) and Earth-Probe (1997-2006) platforms; MODIS instrument on Terra (1999-present) and Aqua (2002-present) platforms

- **Sensor.** Instrument on a specific satellite platform.
  Examples: AVHRR, TOMS, OMI, MODIS, MISR, PARASOL
- **Channel** or **band.** A specific spectral bandwidth where a sensor collects data. Most sensors have multiple (4 to 40) channels.
- **Granule or Scene.** The smallest aggregation of data that is inventoried and retrievable.
- **Distributed Active Archive Center (DAAC).** Center that stores and distributes data.
- **Data Products.** The available sets of data produced by algorithms. Various levels of processing: L1 (raw corrected data), L2 (specific aspect), L3 (time average of L2 data).
- **Pixel:** 2D picture lement

Satellite Orbits

A satellite moving in a circular orbit around the Earth is subject to the balance of the centripetal acceleration and gravitational force, such that

$$F_g = G\frac{M_e m_s}{(r_e + z_s)^2} = m_s \omega^2 (r_e + z_s) \text{ with } \omega = 2\pi / T$$

where G=6.673x10-11N,-2kg-2 the gravitational constant, M_e=5.97x10^{24} kg the mass of Earth, m_s the mass of satellite, ω is the angular velocity of the satellite, r_e=6.38x10^6 m the Earth's radius, and z_s the altitude of the satellite.

Satellites are positioned in on of two orbits: geostationary or polar orbits

- Asynchronous orbits (Keplerian orbits)

Satellite asynchrony witThe altitude of the satellite z_s is fixed and the period T is given by

$$T = \sqrt{\frac{4\pi^2 (r_e + z_s)^3}{GM_e}}$$

- Geostationary orbits

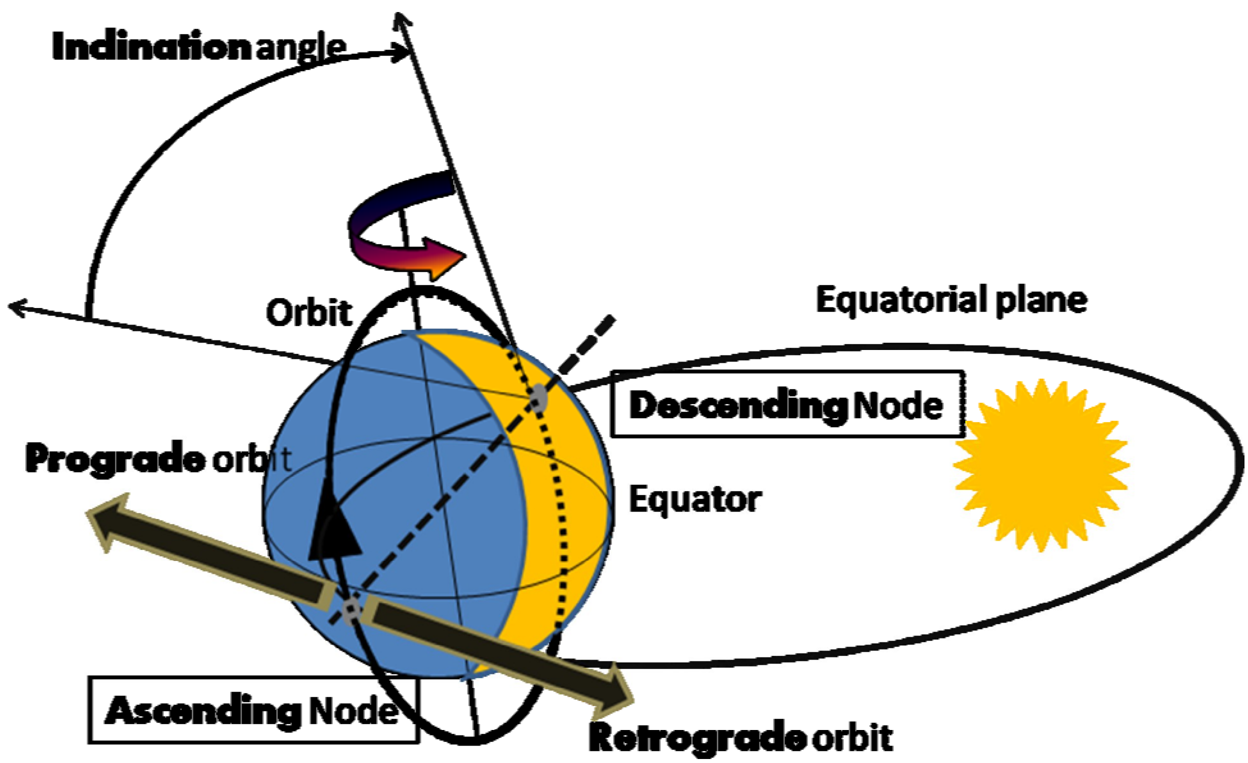
Geostationary satellite observed the time evolution of the same part of the atmosphere. The period is fixed T=24hr and zs is given by

$$z_s + r_e = \left(\frac{GM_e T^2}{4\pi^2} \right)^{1/3}$$

- Polar orbits

Polar orbiting satellite overfly polar region. The poleward extent of the orbit is determined by the angle of inclination. The angle of inclination is the angle measured in the counterclockwise direction between the equatorial plane and the plane of the orbit. Only orbits with inclination greater than 90 degrees cover the entire globe. Nodes are the point of the orbit crossing the equator. If the satellite passes this point northward (southward) then it is an Ascending (Descending) Node.

Sun-synchronous satellite crosses the equator at the same local time every day. Because the Earth rotates around the sun, the satellite orbits drifts. The drift or precession is proportional to the cosines of the inclination and inversely proportional to orbit altitude. So, the precession can be chosen to compensate for the Earth's rotation exactly by adjusting the orbital altitude and the inclination.

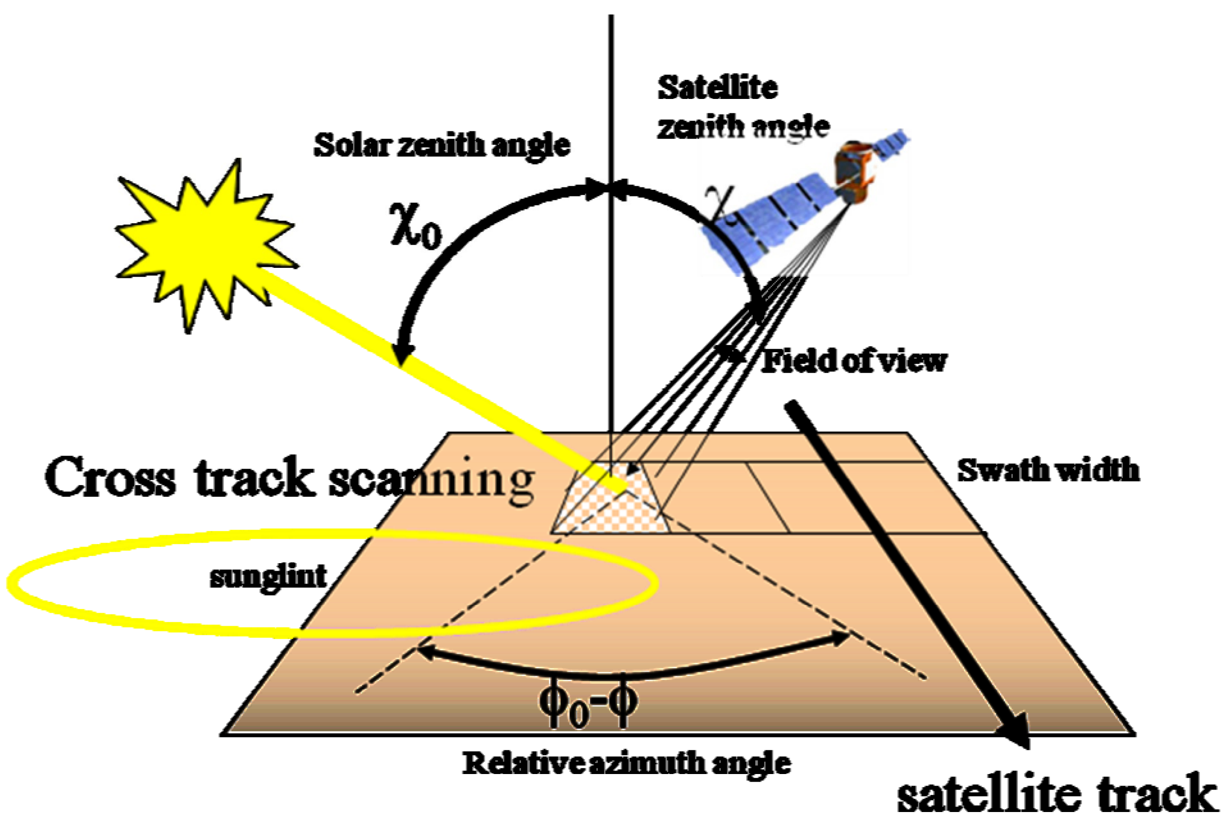


Satellite resolutions

- **Spatial resolution.** The smallest amount of space that a satellite sensor can observe. It depends on:
  - **Field of view**
  - **Altitude**

  - **Viewing angle**
- **Spectral resolution.** The dimension and number of wavelength regions to which sensor is sensitive. The resolution can be:
  - **Broad-band**
  - **Narrow-band**
  - **MultiSpectral:** record multiple bands of the electromagnetic spectrum
  - **Hyperspectral:** record data in hundreds of bands
  - **Ultraspectral:** record data in thousans of bands
- **Radiometric resolution.** It measures the sensitivity of a sensor to differences in the intensity of the measured radiation (i.e. how many grey levels can be distinguished between black and white)
- **Temporal resolution.** The time for a sensor to observe the same location. It is continuous for geostationary and at most daily for polar orbiting

Satellite Geometry



Satellite retrieval from backscatter radiances

We have seen in lecture 4 that the reflectance of solar radiance depends on scattering and absorption of aerosols and molecules, cloud cover, and surface albedo, and can be estimated by the following equation:

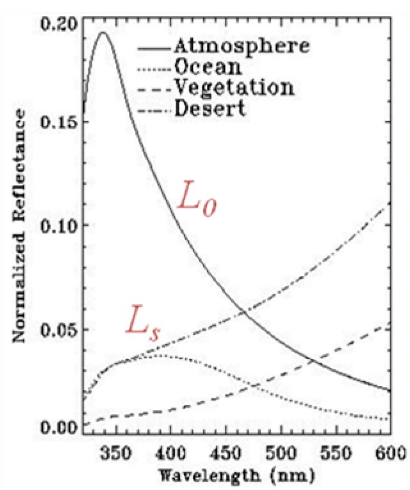
$$L = T_a^2(1 - A_c)\left[(r + \frac{t^2 R_s}{1 - R_s r}) - R_s\right] F_0$$

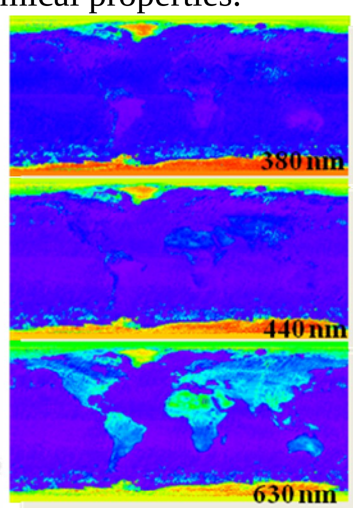
Where T_a is the fractional transmittance, A_c the clouds cover, R_s the surface albedo, $t = e^{-\tau} + \omega(1-\beta)(1-e^{-\tau})$ is the transmitted fraction, and $r = (1-e^{-\tau})\omega\beta$ is the reflected fraction of solar radiation.

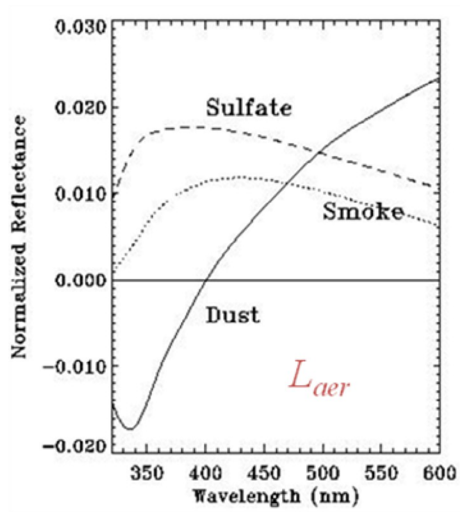
The reflectance at the top of a cloud-free atmosphere is given by the summation of three components:

1. Lo : Rayleigh scattering and gas absorption
2. Ls : Surface reflection
3. Laer : Aerosol scattering and absorption

The magnitude of each component is a function of wavelength. The surface reflection depends on the land cover type. The aerosol component depends on the aerosol physical and chemical properties.







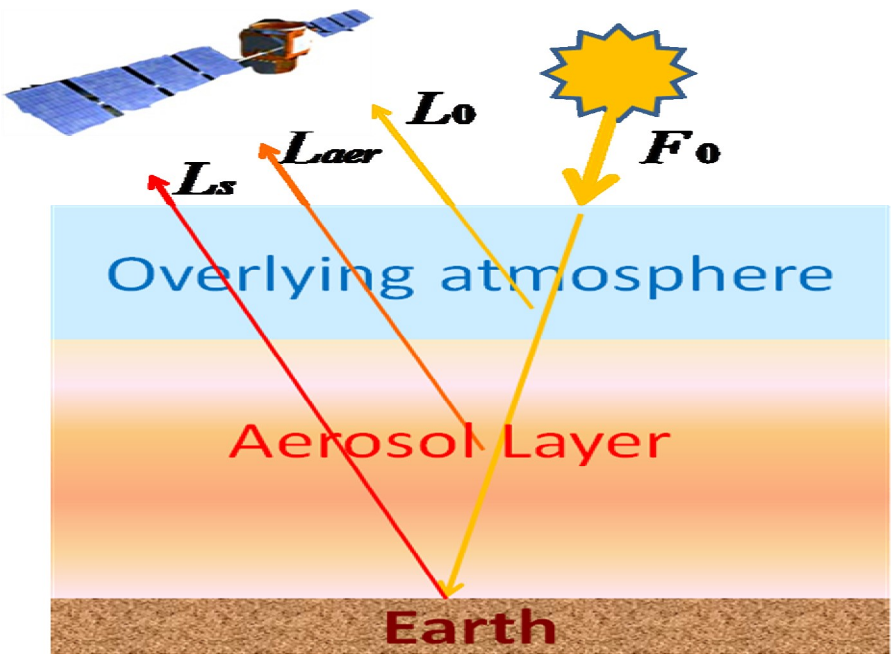
The difficulty is to separate the aerosol contribution L_{aer} from the atmosphere-surface effects (L_o+L_s).

Neglecting aerosol multiple scattering effects, the total reflectance as measured by a satellite is approximately given by

$$L \approx \frac{\omega\, P(\Theta)\pi F_0}{4\pi} \frac{\mu_0}{\mu_0+\mu}[1-e^{-\tau(1/\mu+1/\mu_0)}]+[L_0+L_s]e^{-(1-\omega)\tau(1/\mu+1/\mu_0)}$$

Where ω is the single scattering albedo, $P(\theta)$ is the aerosol scattering phase function, F_o is the solar flux, τ is the aerosol optical depth, and μ, μ_o are the cosines of the satellite and solar zenith angles.

In the right hand side, the first term is the aerosol single scattering contribution, while the second term represents the attenuation of Rayleigh and surface components by aerosol absorption.



Since L_o depends on atmospheric pressure, then

$$L \approx \frac{\omega P(\Theta)\pi F_0}{4\pi} \frac{\mu_0}{\mu_0+\mu}[1-e^{-\tau(1/\mu+1/\mu_0)}]+[\frac{(p_s-p_a)L_0}{p_s}+L_s]e^{-(1-w)\tau(1/\mu+1/\mu_0)}+\frac{p_a}{p_s}L_0$$

where p_s and p_a are the surface and aerosol layer height pressure levels. The net aerosol contribution to the measured reflectance is given by

$$L_{aer} \approx \frac{\omega P(\Theta)\pi F_0}{4\pi} \frac{\mu_0}{\mu_0+\mu}[1-e^{-\tau(1/\mu+1/\mu_0)}]+[\frac{(p_s-p_a)L_0}{p_s}+L_s][e^{-(1-w)\tau(1/\mu+1/\mu_0)}-1]$$

The aerosol single scattering term is only weakly wavelength dependent, while the Rayleigh scattering attenuation is a strong function of wavelength.

AEROSOL RETRIEVALS in the VISIBLE and NIR

In the visible and near-infrared, the Rayleigh scattering component (L_o) is small, and the surface contribution (L_s) from low surface albedo (e.g. oceans) is also small. Therefore, over water surfaces, the aerosol attenuation term is negligible, and there is no sensitivity to aerosol absorption.

Over land, L_s, is generally large and difficult to characterize.

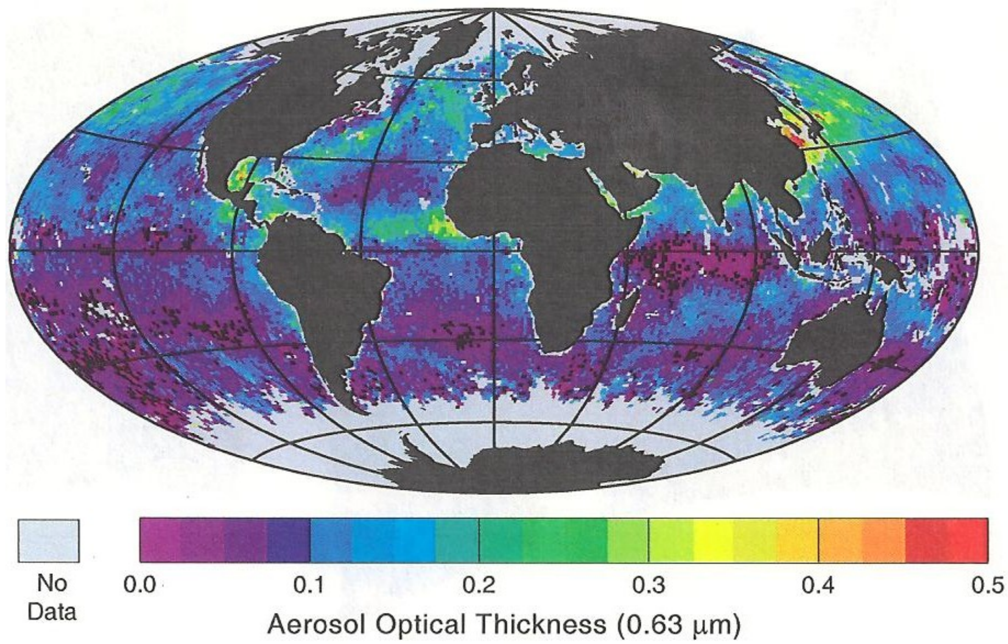
Thus, satellite retrievals of aerosol optical depth in the vis/nIR are only possible over water or dark surfaces, based largely on the aerosol single scattering approximation:

$$L_{aer} \approx \frac{\omega_0 P(\Theta)\pi F_0}{4\pi} \frac{\mu_0}{\mu_0 + \mu}[1 - e^{-\tau(1/\mu + 1/\mu_0)}]$$

Examples:

1. Advanced Very High Resolution Radiometer (AVHRR)

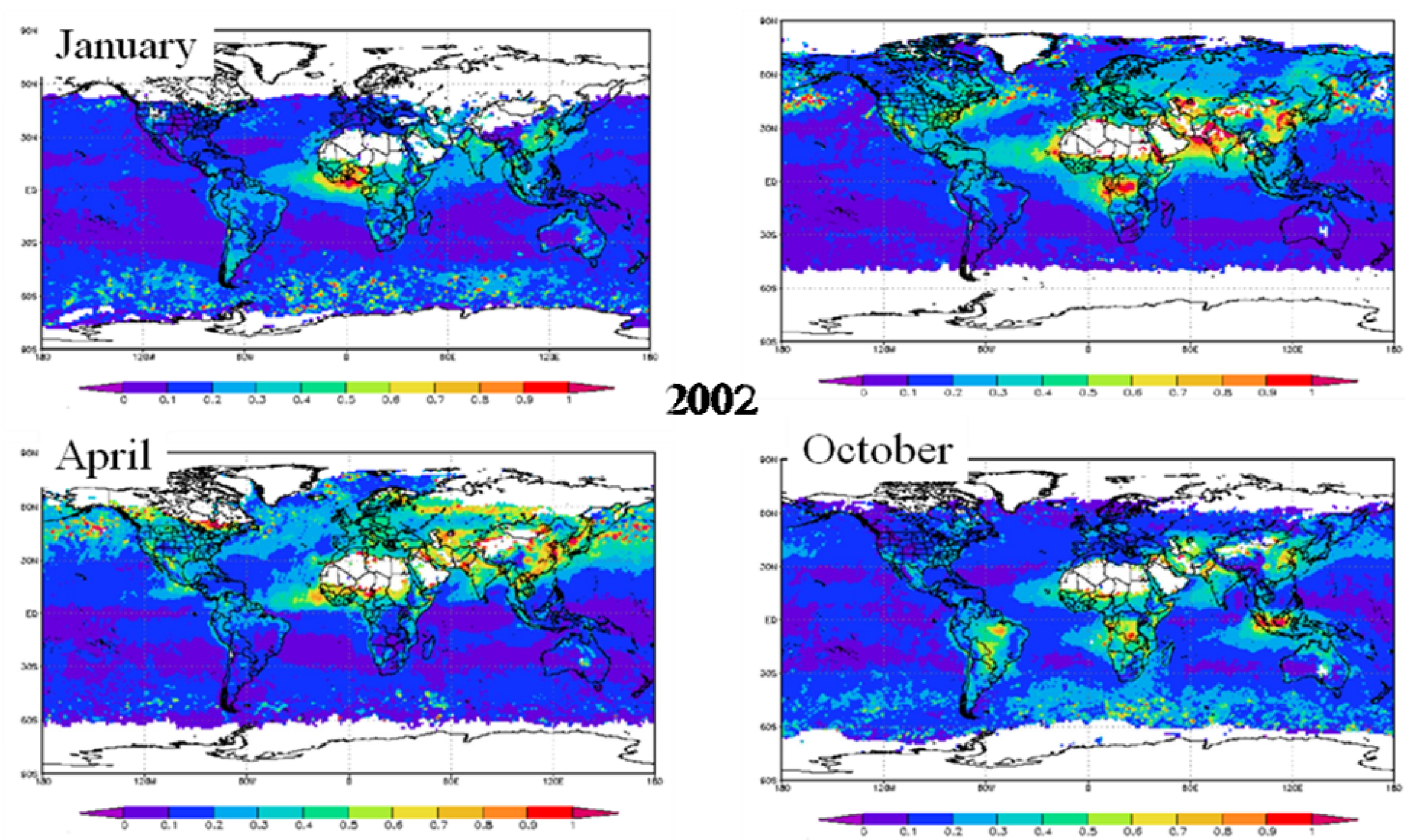
   The AVHRR data have been used to retrieve AOD over ocean at 630nm.



The AOD values from the advanced very high resolution radiometer (AVHRR) with a two-channel algorithm developed by Mishchenko et al. [1999] correspond to the middle to low range of retrieved values. With this algorithm, Geogdzhayev et al. [2002] have retrieved AOD over the ocean from 1981 to 2006 (http://gacp.giss.nasa.gov/data_sets/) As stratospheric aerosols increased the AOD globally after the eruptions of El Chicho´n (March 1982) and Mount Pinatubo (June 1991), Geogdzhayev et al. [2004] used a stratospheric aerosol data from the Stratospheric Aerosol and Gas Experiment (SAGE) instrument to constrain the AVHRR retrieval algorithm. The 2 channels retrieval by Mischenko et al. has been used to assess GFDL global mean AOD over 20 years (cf. http://www.gfdl.noaa.gov/reference/bibliography/2006/png0601.pdf)

2. Moderate Resolution Imaging Spectro-radiometer (MODIS)

The MODIS instrument provides daily almost global coverage of AOD at 550 nm (http://modis-atmos.gsfc.nasa.gov/MOD04_L2/index.html)



AEROSOL RETRIEVALS IN NUV

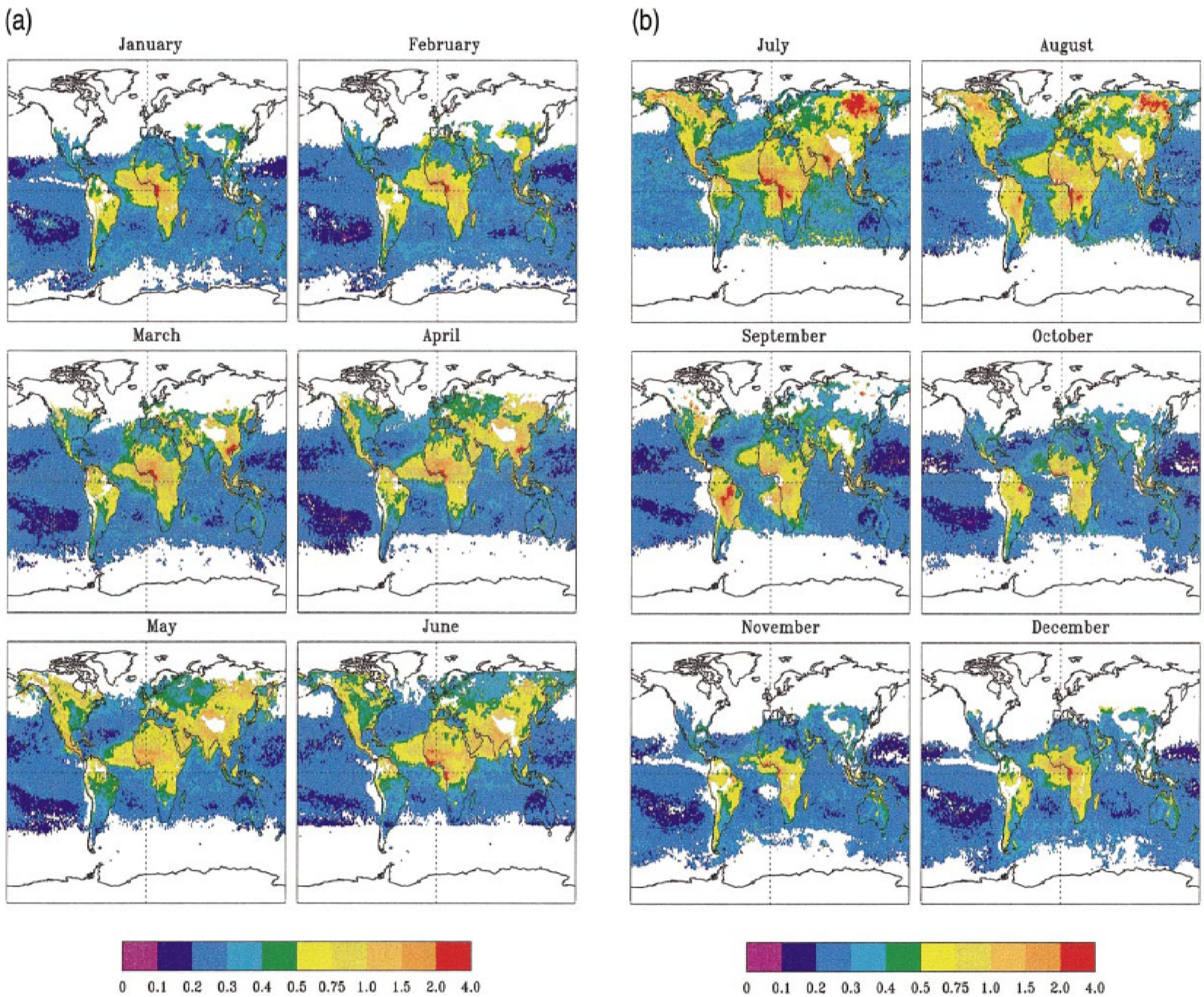
In the near-ultraviolet (330-400nm), the Rayleigh scattering component (L_o) is large and cannot be neglected. Thus, in this spectral region there is significant sensitivity to aerosol absorption. On the other end, the surface contribution is smaller. The aerosol properties can be retrieved over water and land surface surfaces. Due to the dependency of L_o on pressure, the vertical profile of aerosol has to be known.

Example:

Total Ozone Mapping Spectrometer (TOMS)

The first Total Ozone Mapping Spectrometer (TOMS) instrument on Nimbus-7 platform was launched on October 24, 1978; measurements began a week later (http://toms.gsfc.nasa.gov/). Nimbus 7 TOMS failed in 1993 and was replaced in 1996 by Earth Probe TOMS which failed after 20 years (December 2005) on its 500 km polar sun-synchronous orbit (local equatorial passing time: 11:30 am). For the purpose of obtaining daily global maps of atmospheric ozone, TOMS measured the solar irradiance and the backscattered radiances in six wavelengths between 213 and 380 nm (360 nm for Earth Probe). TOMS scanned in 3-degree steps of 51 degrees on each side of the subsatellite point, in a direction perpendicular to the orbital plane. Consecutive cross-scans overlapped, creating a contiguous mapping of ozone. Because of the aerosol absorption in the near UV, TOMS data offers the unique opportunity to study the daily and global distribution of absorbing aerosols (dust and soot) over 2 decades. However there are two difficulties when retrieving aerosol characteristics. First, the large field of view of TOMS instrument (50 × 50 km at nadir, 150 × 250 km at extreme off nadir) almost always contains subpixel clouds. This problem can be minimized by using several wavelength channels. Second, the sensitivity of aerosol absorption to molecular scattering and height necessitates the knowledge of the aerosol vertical profiles. Due to the lack of data providing global vertical distribution of aerosols, retrieval algorithms use simulated aerosol distribution from global models.

The figure below shows the long-term (1979-1991) global monthly average aerosol optical depth derived from NIMBUS-7-TOMS data (http://www.gfdl.noaa.gov/reference/bibliography/2002/torres0201.pdf).


(a)
January
February
March
April
May
June
0 0.1 0.2 0.3 0.4 0.5 0.75 1.0 1.5 2.0 4.0
(b)
July
August
September
October
November
December
0 0.1 0.2 0.3 0.4 0.5 0.75 1.0 1.5 2.0 4.0

Specs of aerosol satellite instruments

Instrument	Spacecraft	Spatial resolution (km)	Swath width (km)	Sensor characteristics	Comments
AVHRR	*NOAA-7, -9, -11, -14,* -L, Metop-1	1.1 (local mode); 4.4 (global)	2800	Cross-track scanner with five spectral bands	Relatively long-term dataset (since 1979); limited calibration accuracy (no internal calibration); near-infrared band influenced by water vapor absorption
TOMS	*Nimbus-7, Meteor-3,* ADEOS, Earth Probe, QuikTOMS	50	3000	Fixed-grating monochromator resolves incoming light into six bands	Relatively long-term dataset (since 1978); sensitive to absorbing aerosols over land and ocean; lower spatial resolution than comparable imaging radiometers
ATSR-2	*ERS-2*	1	500	Conical scanner with two views of the earth (forward look angle of 55°, and near nadir), separated in time by 2 min; seven spectral bands	Multi-look-angle sensor not specifically designed for aerosol retrievals; narrow swath width, taking 6 days for global coverage
OCTS	ADEOS	0.7	1400	Cross-track scanning radiometer with 12 spectral bands; tilt capability (±20°) to avoid sun glint	Has three thermal channels that can be used for cloud screening; no onboard calibrators; requires resampling for registration of bands
POLDER	ADEOS, ADEOS II	7×6	2200	Bidimensional CCD matrix and rotating wheel that carries filters and polarizers with a large field-of-view (114°) lens	Polarization more sensitive to aerosol refractive index than radiance; observes earth targets from 12 directions; uses A-band, reflectance thresholds, and spatial coherence for cloud screening; no onboard calibrators
SeaWiFS	OrbView-2	1.1 (local mode); 4.5 (global)	2800	Cross-track scanning radiometer with eight spectral bands; tilt capability (±20°) to avoid	Has no thermal channels for cloud screening; solar and lunar maneuvers for

Instrument	Spacecraft	Spatial resolution (km)	Swath width (km)	Sensor characteristics	Comments
MISR	Terra	1.1	360	Nine CCD-based pushbroom cameras viewing nadir and fore and aft up to 70.5°; four visible and near-infrared bands	Has no thermal channels for cloud screening; uses high quantum efficiency diodes for in-flight calibration; takes 9 days for global coverage
MODIS	Terra, EOS PM	0.25–1	2330	Cross-track scanning spectro-radiometer with 36 spectral bands	High calibration accuracy with many onboard calibrators and wide spectral range; ability to detect clouds, shadows, and heavy aerosol
AATSR	Envisat-1	1	500	Conical scanner with two views of the earth (forward look angle of 55°, and near nadir), separated in time by 2 min; seven spectral bands	Multi-look-angle sensor not specifically designed for aerosol retrievals; no onboard calibrators
MERIS	Envisat-1	0.3–1.2	1150	Cross-track scanner with tilt capability; 15 bands acquired and transmitted in flight	Oxygen A-band capability for cloud top altitude determination; no SWIR or thermal bands
GLI	ADEOS II	0.25–1	1600	Cross-track scanning spectro-radiometer with 36 spectral bands	Wide spectral coverage with many bands at 250 m (locally available); ability to detect clouds, shadows, and heavy aerosol; inclusion of absorbing aerosol bands in the UV
OMI	EOS CHEM	13 (local mode); 13 × 24 (global)	2600	Wide field telescope feeding two hyperspectral pushbroom grating spectrometers with 740 spectral bands from 270 to 500 nm	High calibration accuracy with many onboard calibrators; no thermal channels for cloud screening